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13. ABSTRACT (Maximum 200 words)

The major objective of the research reported was to study the properties of constant scalar property surfaces in turbulent reacting flows. Two-dimensional image measurements were made in premixed turbulent flames and in jets and jet flames Point-in-space, time-series measurements were also made, and the data used to study the properties of surface crossing statistics in jets and premixed flames. In addition, the hypothesis that, for the purpose of estimating the mean surface area per unit volume, surfaces in turbulent flow can be represented by fractal surfaces was used to develop models for the mean chemical reaction rate in premixed flames and for the source term in the equation for intermittency in free jets. Also a new method for making conditional velocity measurements in premixed flames was developed and applied to obtain unique data for velocity in these flames and to study jumps, across flamelets, of certain velocity statistics.

Major findings for the flows and conditions studied include: 1) for the premixed case flamelet surfaces are fractal as are constant mixture fraction surfaces in jets and constant temperature surfaces in jet flames; 2) in jets the surface fractal dimension is between 2.3 to 2.4; 3) level crossing sets from time-series data are not simple fractal sets; 4) the idea of "fractal bursts" is introduced to help interpret the crossing sets; and 5) unique "fully"-conditional velocity data give a measure of velocity jumps across flamelets in premixed combustion.

14. SUBJECT TERMS
Premixed turbulent combustion, flamelets, fractals, laser doppler velocimetry, compensated thermocouples, Rayleigh scattering

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AN EXPERIMENTAL STUDY

OF

FLAMELET SURFACES IN TURBULENT COMBUSTION

FINAL REPORT

F. C. GOULDIN

DECEMBER 28, 1990

U. S. ARMY RESEARCH OFFICE

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A. STATEMENT OF PROBLEM

The major objective of the research reported here was to study properties of constant scalar property surfaces in turbulent reacting flows. Two-dimensional image measurements were made in premixed turbulent flames and in jets and jet flames. Point-in-space, time-series measurements were also made, and the data used to study the properties of surface crossing statistics in jets and premixed flames. In addition the hypothesis that for the purpose of estimating the mean surface area per unit volume surfaces in turbulent flow can be represented by fractal surfaces was used to develop models for the mean chemical reaction rate in premixed flames and for the source term in the equation for intermittency in free jets. Also a new method for making conditional velocity measurements in premixed flames was developed and applied to obtain unique data for velocity in these flames and to study jumps, across flamelets, of certain velocity statistics. This research is described and results discussed in this report.

B. SUMMARY OF RESULTS

2-Dimensional Image Measurements

In these experiments Mie scattering from a sheet of laser illumination was photographed by a 35 mm still camera to obtain two-dimensional images of the scattering field. The seed for the scattering was an oil mist which evaporates at modest temperatures, approximately 650 K, and therefore marks the reactant in premixed flames, the jet fluid in jet mixing flows and low temperature, fuel-rich fluid in jet flame studies. In these three cases the boundary between marked and unmarked fluid corresponds to 1) the flamelet, 2) the super layer[1] (the boundary between turbulent and non-turbulent fluid) and 3) the 650 K fuel-rich isotherm. The data obtained in these experiments were photographs in which cuts (intersections) of the boundary surfaces with the plane of the illuminating laser sheet can be identified. These curves were digitized by hand with a digitizing tablet and then the curves were analyzed for fractal behavior using a box counting algorithm. During the course of the investigation this algorithm was refined and improved, but the conclusions reached on the basis of the analysis results are independent of the exact algorithm form. The results of these measurements are presented in several reports [1, 2], a thesis [3] and a publication [4].

The results of the image studies can be summarized as follows:

Premixed flames: If a curve on a plane is given as a set of points, S, then a measure of this set is the number N of boxes of size ε which cover the set. For simple fractal behavior $N \sim \varepsilon^{D-1}$, where D is the fractal dimension and $1 \leq D < 2$. Surfaces in turbulent flow are not expected to exhibit fractal behavior for all length scale but rather for a range [5, 6] between an inner cutoff, ε_i, and an outer cutoff, ε_o. To assess fractal behavior we apply a

[1] Since droplets do not diffuse as does vorticity and molecules the bounding surface is not exactly the super layer. Exactly how large is the difference between the super layer and the surface marked at this time is unknown although we expect that it is small. Since the oil evaporates at a well defined temperature there is no corresponding ambiguity in the surfaces marked in the premixed flame case nor in the jet flame case provided there is not significant local quenching of reaction which might allow unreacted, fuel-lean pocket of fluids to form.

box counting algorithm to determine N versus ε and then plot the results as log N versus log ε to see if there is a region in which a power law relationship between N and ε exists. If such a region does exist then in principle one can determine D, ε_i and ε_0.

Measurements were made on methane-air, V-flames for different mixture ratios and different reactant flow velocities. Fractal behavior was observed for a range of ε. D values for the curves were about 1.1; the outer cutoff was proportional to the integral scale of the turbulence in the reactant flow; and because of a lack of spatial resolution and noise in the measurements it was not possible to determine the inner cut off.

Fractal measurements have now been made in several different flames, - V-flames, bunsen flames, and free flames - and in spark ignition engine flames by different investigators, e.g., References 4 and 7 - 10. The results of these measurements can be summarized. Log N versus log ε plots have nearly straight line segments indicating fractal behavior. The measured fractal dimension varies with conditions and approaches a limit of 2.3 to 2.4 as the turbulence becomes more intense. The limit is consistent with the fractal dimension of passive scalar surfaces in turbulent flow as observed by Sreenivasan and co-workers [11, 12] and as predicted by modeling studies [13, 14]. North and Santavicca [7] have suggested a correlation for the variation of D which does a reasonable job of correlating the results available to date.

While all results for D are reasonably consistent, such is not the case for the cutoffs. Some investigators conclude that the outer cutoff scales with turbulence length scales, e. g., the integral scale, while others find that it scales with the burner size. Because of insufficient spatial resolution and, possibly, signal-to-noise problems less can be said about the inner cutoff and considerable debate continues over what is the nature of the inner cutoff and its relationship to the Kolmogorov and Gibson scales. Determination of the cutoffs which are expected to be related to the maximum and minimum scales of wrinkling is of general interest and is a challenging problem. For the inner cutoff good spatial resolution and high signal-to-noise measurements are need. On the other hand a large data set is needed to compute appropriate averages, i. e., a large field of view is required. For electronic detection very large arrays which are becoming only now available, are needed to obtain both large data sets and fine scale resolution. Another problem in the determination of the cutoffs is that in many of the flows studied lengths scales vary in space and therefore the cutoffs are expected to vary in space. Thus there are conflicting requirements in the measurement of fractal properties which appear to be incompatible.

Non-premixed jet flames: The same method as described above was used to studying burning and non-burning jets [2, 15]. In the case of the non-burning jets the surface observed was near the interface between turbulent and non-turbulent fluid, while in the burning case the surface was a 650 K isothermal surface on the fuel-rich side of the stoichiometric mixture fraction surface. These measurements gave equivalent results. On log N versus log ε plots fractal like regions were observed with D found to be between 2.3 and 2.4. The outer cutoff appeared to scale with the integral scale, while the inner cutoff could not be determined. Sreenivasan and co-workers, e.g., References 11 and 12, have performed extensive image measurements on non-reacting shear flows. Our results are entirely consistent with their results.

Initially we had hoped to be able to study the fractal character of high temperature surfaces by using particulates that sublime at high temperatures. Unfortunately seeding difficulties prevented such measurements.

Point-in-Space, Time-Series Measurements

As noted above, lack of resolution, signal-to-noise problems and the need for large data sets hampered the fractal analysis of image measurements. In jet flames images of high temperature surfaces could not be obtained. Time-series measurements were undertaken to circumvent some of these problems. In addition time series measurements allow for the determination of surface crossing frequencies and passage time distribution functions, properties which appear implicitly or explicitly in several source term closure models [16, 17].

The set of points defined by the intersection of a surface and a curve is here defined as an intersection set ant if the surface is fractal and the curve smooth (nonfractal) the intersection set will be fractal. For a time-series signal, the times when the signal obtains a certain value forms a level crossing set. If that certain value, e.g., temperature, defines a surface and Taylor's frozen flow hypothesis is taken literally then one expects a relationship to exist between the level crossing set of the time-series signal and the intersection set of the related surface. Thus there is an expectation that time series measurements can be used to study the fractal characteristics of surfaces in turbulent flow. This expectation is built upon a literal interpretation of Taylor's hypothesis which in this case is not valid.

Measurement Methods: Several experimental methods were employed in these studies. First in premixed flames measurements of laser scattering from an oil mist were performed [4, 18]. While preliminary results were encouraging, later experiments [19] showed that limited spatial resolution and marker shot noise associated with large droplets influenced the results precluding the possibility of finding the inner cutoff and affecting the measured D values. A refined compensated thermocouple method was then developed which gave much better spatial and temporal resolution [20 - 21]. The important features of the refined method are low noise amplification prior to 12 bit A/D conversion and digital filtering before differentiation for compensation. In addition a new method for finding the time constant was developed which gives very good results [21] and which shows that for the conditions studied the time constant is almost constant over the reaction zone.

Rayleigh scattering was used for jets and jet flames [3]. The system consisted of an Argon ion laser (1.5 w at 488 nm), large aperture collection optics with polarization filter, and 3/4 meter monochromator equipped with a photomultiplier. The signal from the photomultiplier was filtered, digitized and stored for analysis. Measurements were made in jets and jet flames. From the digitized data, after additional filtering, level crossing sets were obtained and analyzed for fractal behavior.

The results of measurements in premixed flames and jets can be summarized as follows.

Premixed flames: From the temperature record level crossing sets were obtained for a temperature of 1200 K; the occurrence of this temperature was used arbitrarily to define the passage of the flamelet - a flamelet cross event. Level crossing sets were analyzed to obtain flamelet crossing frequencies, pdf's of passage times (the times between passage events), both unconditional and conditional in reactants and products, and to evaluate fractal behavior. A box counting algorithm was employed for the fractal evaluation. Plots of both logN versus log ε, and the slope of this curve (as suggested by Miller and Dimotakis [23]) were constructed and studied.

The crossing frequency data are consistent with the passage time closure model [16] and the fractal model [17] but are not extensive enough to allow for a full evaluation of these models. The crossing frequency is proportional to the product of the mean progress variable and one minus the mean progress variable divided by a time scale which in turn scales with the turbulent flame brush thickness.

The pdf's are a good indicator the quality of the data. The maximum in the pdf is found to occur at very short times, while at the shortest times measured there is a spurious peak in the pdf due to noise. If the data are of good quality there is a clear separation of the maximum in the pdf and the noise peak at shorter times. For pdf's obtained by laser scattering such separation was evident, while for the thermocouple data there is a distinct separation. The thermocouple data show that the conditional pdf's are represented reasonably well by the Gamma II distribution proposed by Bray, et al. [21, 24].

The results of the fractal analysis are somewhat ambiguous. Plots of minus the slope, d, of the logN versus logε curve show at best a narrow region of constant d and this range is for the smallest ε. Furthermore d in this range is very small implying a fractal dimension for the surface which is very close to 2 and is somewhat dependent on the amount of filtering of the data [20, 21]. To explain these results we have introduced the hypothesis of "fractal bursts" [21] which is discussed below.

Jets and jet flames: Rayleigh data were collected for several different jet conditions. Unfortunately signal-to-noise ratios for burning conditions were lower than for non-burning and only the results for jet mixing can be analyzed in detail. From the Rayleigh data, level crossing sets were obtained and analyzed for fractal behavior. Plots of d versus log ε were found to be most helpful and such plots were made for a range of level crossing sets. Typical results are shown in Figure 1.

Several features of the d curves and their variation with signal level should be noted. Most striking is the lack of an obvious fractal region, i.e. a plateau or constant d region. Also striking is the variation in the curves with crossing level. When the crossing level is set equal to the mean value of the signal there is a near monotonic decrease in d from 1 to zero as ε decreases. While the limiting behavior for large and small ε is expected, the lack of apparent fractal behavior is surprising given the fact that the the two-dimensional image data indicate that the surfaces are fractal. For crossings set levels increasing different, either larger or smaller, than the mean value, the d curves develop a broad hump with a maximum value of d around 0.3 to 0.4. This is interesting because the intersection set generated from a isotropic fractal surface of dimension D_3 is D_3 - 2, and therefore this local maximum in d is the value expected for a crossing set from the image measurements. From these Rayleigh results we concluded that the level crossing sets obtained from time series data are not simple fractals.

Miller and Dimotakis [23] report on measurements in water jets in which the fractal character of level crossing sets is studied. Their measurements are made with great care and a much larger signal-to-noise ratio is obtained in their measurements than was possible in the present jet measurements. However their results are qualitatively similar to the present results. No simple fractal behavior is observed, and d curves develop a local maximum as the level crossing value defining the set diverges from the signal mean. Sreenivasan and Meneveau [11] also make time-series measurements. They analyze small sets and conclude that fractal behavior is observed, while Sreenivasan and Prasad [12] in later work appear to back away from the conclusion that fractal behavior is observed in level crossing sets from time-series data. From our observations and those of Miller and Dimotakis we conclude as stated that simple fractal behavior is not observed in level

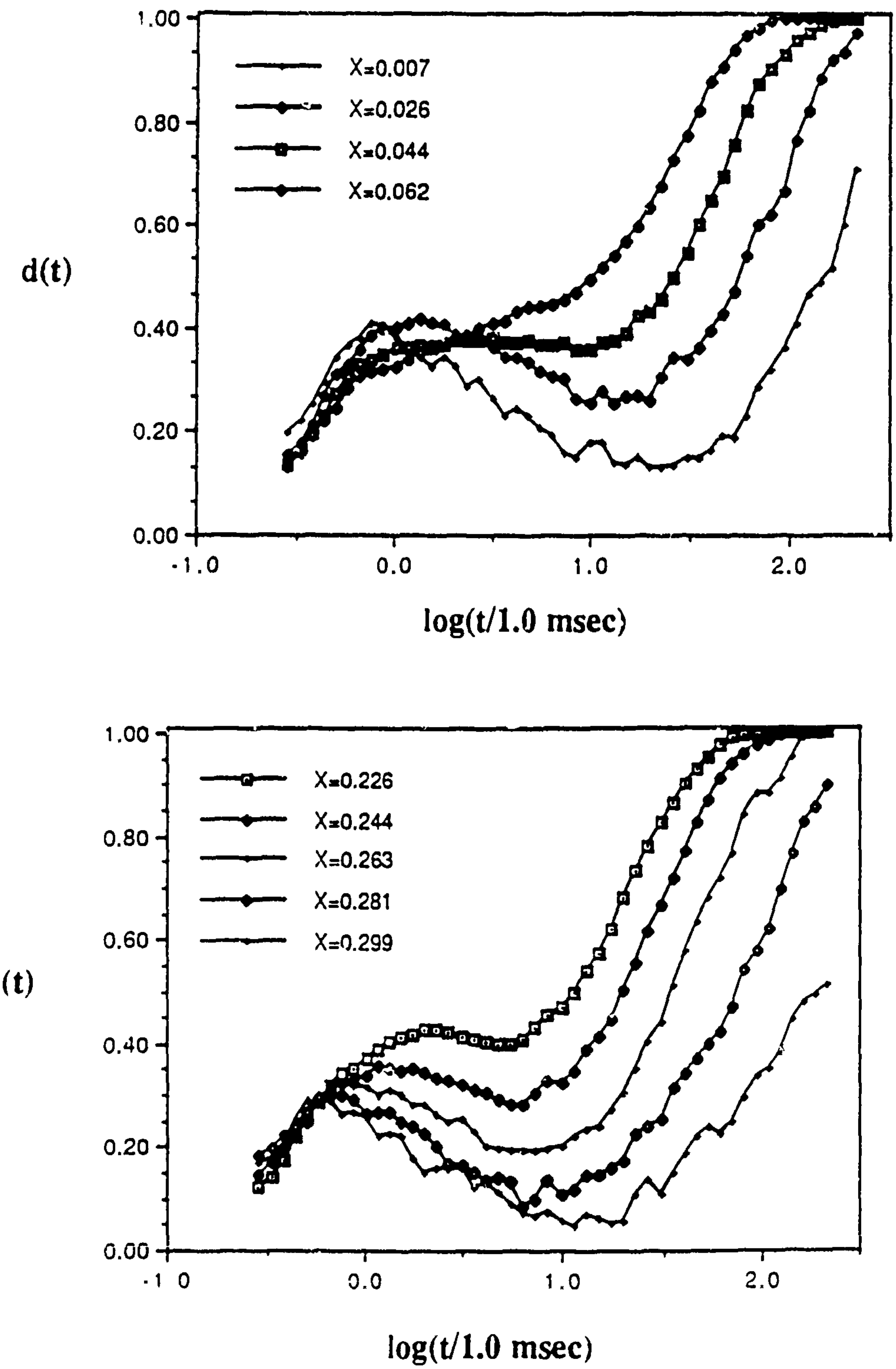
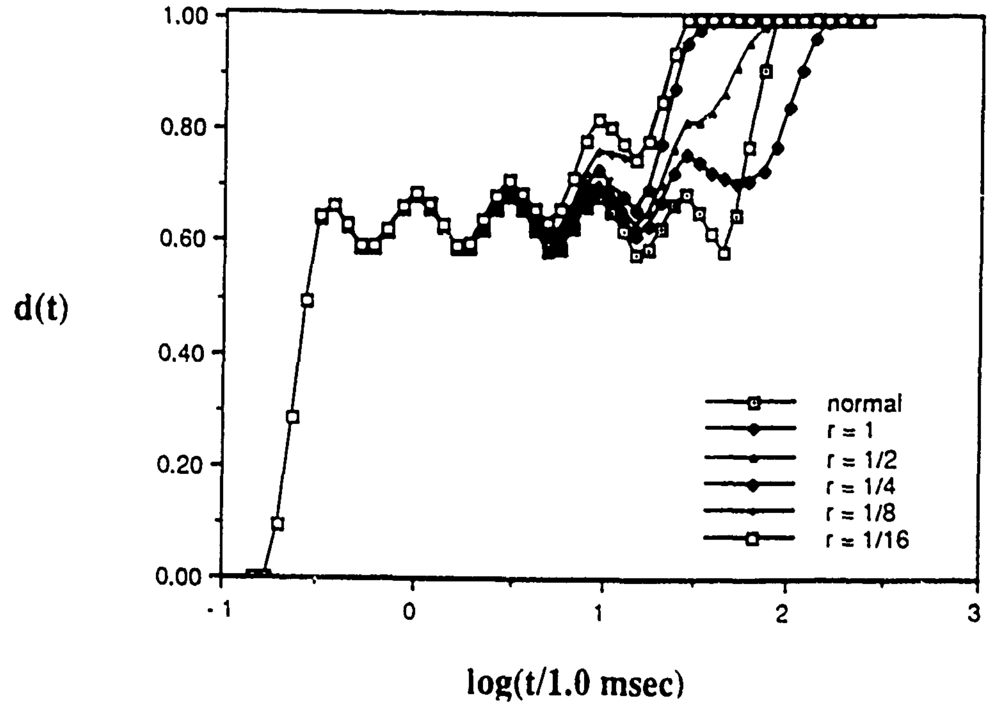


Fig. 1. d plots for different level crossing sets in a jet flow. X is the jet fluid mole fraction.



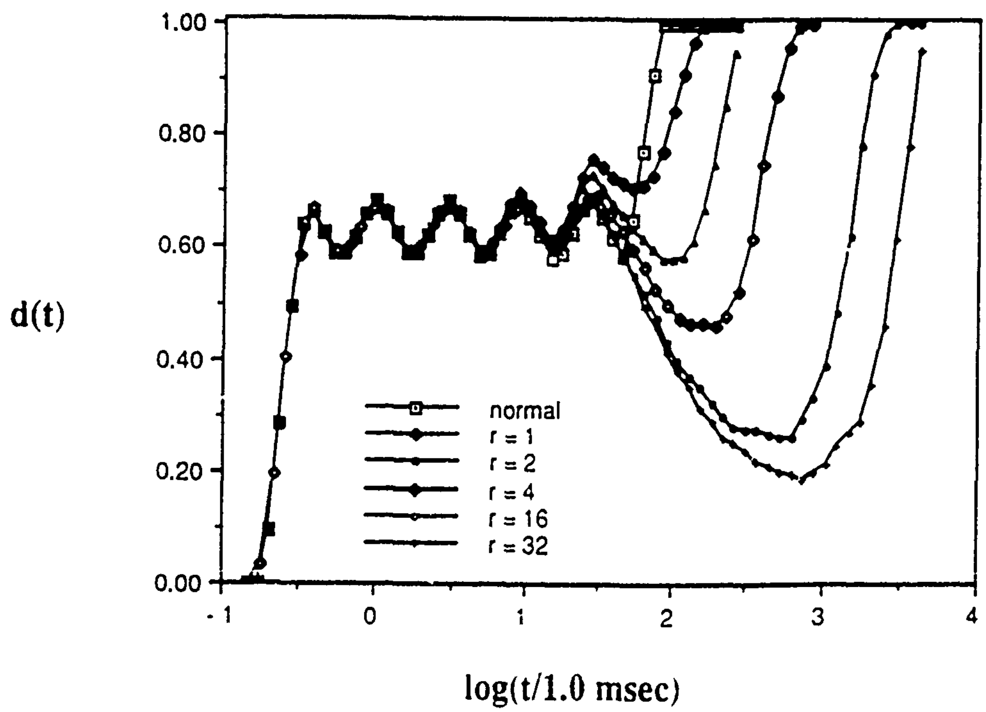


Fig. 2. d plots from fractal burst simulations.
r is the ratio of the mean spacing between fractal bursts and the burst length, which is defined as 60.75 ms long. Each burst is a Cantor dust with 64 members.

crossing sets. How then are these results to be reconciled with the image data that support the hypothesis that constant property surfaces in turbulent flows are fractal ?

The expectation that level crossing sets should be fractal is based on the assumptions that surfaces are fractal and that Taylor's hypothesis is valid over the time record. We believe that the latter assumption is not valid, and we state, as obvious, that the frozen flow hypothesis should at the very least not hold over times much longer than the order of the integral time scale which in the present case and in the case of the Miller and Dimotakis work is short compared to the lengths of the time records analyzed. Long and co-workers [25] have obtained by laser induced scattering methods sequences of two-dimensional images separated in time by small increments. It Taylor's hypothesis were sufficiently valid to directly relate the fractal properties of level crossing sets to the fractal properties of surfaces, then these sequences of images should be identical except for translation of the images in the flow direction from one frame to the next. The images obtained by Long and his co-workers are not such sequences, and therefore Taylor's hypothesis cannot be invoked to develop a simple link between level crossing sets and intersection sets.

While there is no simple relationship between the two sets, there is reason to believe that some relationship exists. Gouldin, et al [17] have proposed a chemical closure model for premixed turbulent flames based on the assumption of fractal flamelets. Gouldin [26] has considered the implications of this model for flamelet crossing sets. He notes that the crossing frequency must vary across the flame brush and that if the crossing set were a simple fractal set in the scale range defined by the inner and outer cutoffs then these cutoffs and/or D must vary across the flame brush. Since these variations are consistent with a fractal surface, Gouldin conjectures that the crossing set is a union of two sets, one fractal and one non-fractal. Furthermore Gouldin suggests that the non-fractal set is associated with passage times which are all larger than those associated with the fractal set.

Gouldin's idea has been elaborated in References 3 and 21 where it is referred to as "fractal bursts". The fractal set of crossing events is composed of many small subsets of fractally distributed crossing events with each subset distributed non-fractally in time. Each small subset is a "fractal burst", and it is suggested that for a burst Taylor's hypothesis is valid for relating a short in time crossing set to a short in space intersection set. These "fractal bursts" are distributed non-fractally in time, and one may speak of "fractal bursts" on a non-fractal support. It is assumed that the idea of "fractal bursts" is applicable to the flows studied - to jets, jet flames and to premixed flames.

To lend this hypothesis support Riley [3] has performed a series of numerical simulations of "fractal bursts", the results of which are quite suggestive. Riley's bursts are identical Cantor dusts [5] which are distributed randomly in "time". He performed a series of calculations in which the mean spacing between bursts were varied, while the length of an individual burst was fixed. Simulated crossing sets were analyzed in the same way the level crossing sets were analyzed. In Figure 2 his results for d are presented for different mean spacing between bursts. There are some significant similarities between Figures 1 and 2.

First note that the dimension of the Cantor dust used is 0.66, and in all cases there is a plateau in the simulation results corresponding to this value[2]. The important similarities are in how the curves vary as the time scale between busts is varied. For large times there is a local maximum in the d curves similar to those seen in Figure 1 for levels

[2] The oscillations are due to the fact that the dust is simulated to a fixed, finite scale. Therefore the oscillations have no significance.

far removed from the mean. As the time between bursts is decreased the local minimum in the curve disappears and then the outer cutoff decreases with further reductions in mean separation time. In these simulations even with a very small mean separation time a fractal plateau is still observed. In these calculations the bursts were identical. It seems reasonable to expect that if the bursts varied in length and were random fractals the plateau regions might disappear all together as the mean separation time was decreased. Also on physical grounds it is seems reasonable to expect that as the level defining a crossing set varies from the mean value the number of "fractal bursts" over a fixed time period would go down and the mean time between bursts would increase. Thus the trends in the experimental data are plausibly explained by the simulation results.

The term multifactal is used to denote complex fractal sets which are the union of simple fractal sets [27]. Here simple refers to sets with the same fractal dimension when the dimension is calculated using different definitions, while complex refers to sets where different definitions give different dimensions. At this time we do not see that our "fractal bursts" are an example of a multifractal. The difference being that in the case of multifractals each definition when applied to the set gives a fractal result but of different fractal dimension while in the "fractal burst" case depending on the relationship of the non-fractal support to the fractal set or sets the box counting algorithm may give non-fractal results.

To summarize, image data support the hypothesis that flamelets and constant scalar property surfaces in shear flows are fractal. Point-in-space, time-series measurements are inconsistent with this result. The inconsistency is explained by the inapplicability of Taylor's frozen flow hypothesis; that is the two measurements are not expected to be consistent. The hypothesis of "fractal bursts" is introduced to establish a link between time and image measurements. The hypothesis is supported by physically based, heuristic arguments and by the results of numerical simulations. At this point it must be concluded that the fractal properties of surfaces are best investigated by image measurements. Time-series measurements are still of value for many reason including their relative ease and the relationship between crossing frequency and source term closure models.

Fractal Based Soucre Term Modeling

The source term in the governing equation for the intermittency, γ,which is the local probability of turbulent flow being present in a shear flow and is the mean of the indicator function, I, can be expressed as $\langle V^c \Sigma \rangle$, where the angle brackets denote ensemble mean, V^c is the speed of the super layer with respect to the non-turbulent fluid, and Σ is the instantaneous super layer surface area per unit volume [29]. If $\langle V^c \rangle$ is the mean of V^c and correlations between V^c and Σ are neglected than the source term can be expressed as $\langle V^c \rangle \langle \Sigma \rangle$ where $\langle \Sigma \rangle$ is the mean of Σ. Also note that $\langle V^c \Sigma \rangle$ has the units of frequency and should scale with the super layer crossing frequency. In Ref. 30 $\langle V^c \Sigma \rangle$ is modelled by an expression of the form $A\gamma(1-\gamma)$ where A is a function of various properties of the turbulent velocity field. Similarly the chemical source term in the equation for the mean progress variable, $\langle c \rangle$, in the flamelet limit of premixed turbulent combustion can be expressed in the same form as that for γ except that V^c is the strained laminar burning velocity, u_L, and the term is multiplied by the reactant mixture density. Using the obvious analogy between the source terms in the equations for γ and for $\langle c \rangle$, we have developed fractal based closure models for both terms.

The model for premixed flames is presented in detail in Reference 17. The source term expression is

$$<\omega> = \rho_r <u_L>_f C\, (\varepsilon_o/\varepsilon_i)^{D-2} <c>(1 - <c>) / l_f,$$

where u_L is the burning velocity, f denotes average over the flamelet and $<\Sigma>$ is given by

$$C\, (\varepsilon_o/\varepsilon_i)^{D-2} <c>(1 - <c>) / l_f.$$

C is a model constant of order one and l_f is the turbulent flame brush thickness. The results of preliminary calculations using this closure model are quite encouraging [17].

By analogy a fractal based closure model for the source term in the transport equation for γ is proposed. Specifically, it is suggested that the source term be modeled by

$$W\gamma = C_d\, v\, (\varepsilon_o/\varepsilon_i)^{D-2} \gamma (1 - \gamma) l_\gamma^{-1}.$$

$W\gamma$ is the source term for incompressible flow; C_d is an empirical constant; and v is the Kolmogorov velocity. ε_o and ε_i are the inner and outer cutoffs, and D is the fractal dimension. γ is the intermittency, and l_γ is the thickness of the intermittent layer. To obtain this expression from the corresponding expression in 17, γ replaces <C> and v replaces the mean of the strained laminar burning velocity.

v, ε_o and ε_i are conditional quantities evaluated in the turbulent fluid. With typical scaling

$$v = A_t^{1/4} R_l^{-1/4} u' \;,$$

where A_t= constant; R_l ($R_l = u'l/\nu$) is a conditional turbulence Reynolds number; and u' is a conditional turbulence intensity. Assume $\varepsilon_o = l$ and $\varepsilon_i = \eta$ (the conditional integral and Kolmogorov scales) and with typical scaling $l/\eta = A_t^{1/4} R_l^{3/4}$.

If one substitutes into the expression for W_γ these relationships for $\varepsilon_o/\varepsilon_i$ and for v one obtains

$$W_\gamma = C_d A_t^{1/4(D-1)} R_l^{3/4(D-2)-1/4} u'\gamma(1-\gamma) l_\gamma^{-1} .$$

And for D = 2 1/3 the R_l dependency is removed since 3/4 (D-2) - 1/4 = 0.

$$W_\gamma = C_d\, A_t^{1/3} u'\, \gamma(1-\gamma) l_\gamma^{-1}$$

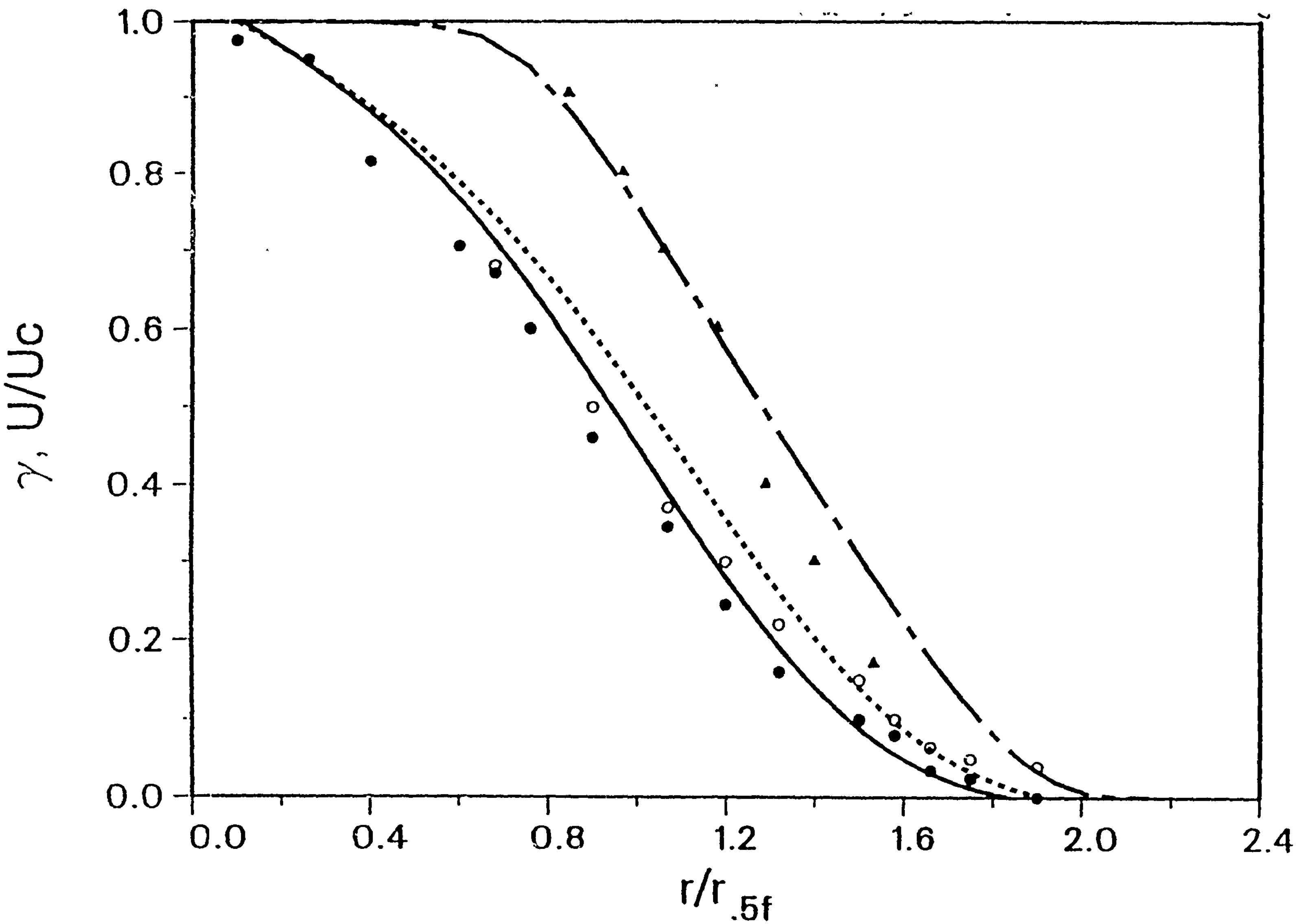


Fig. 3 Radial profiles of axial mean velocity, conditional (---------) and unconditional (- - - -) and of γ.

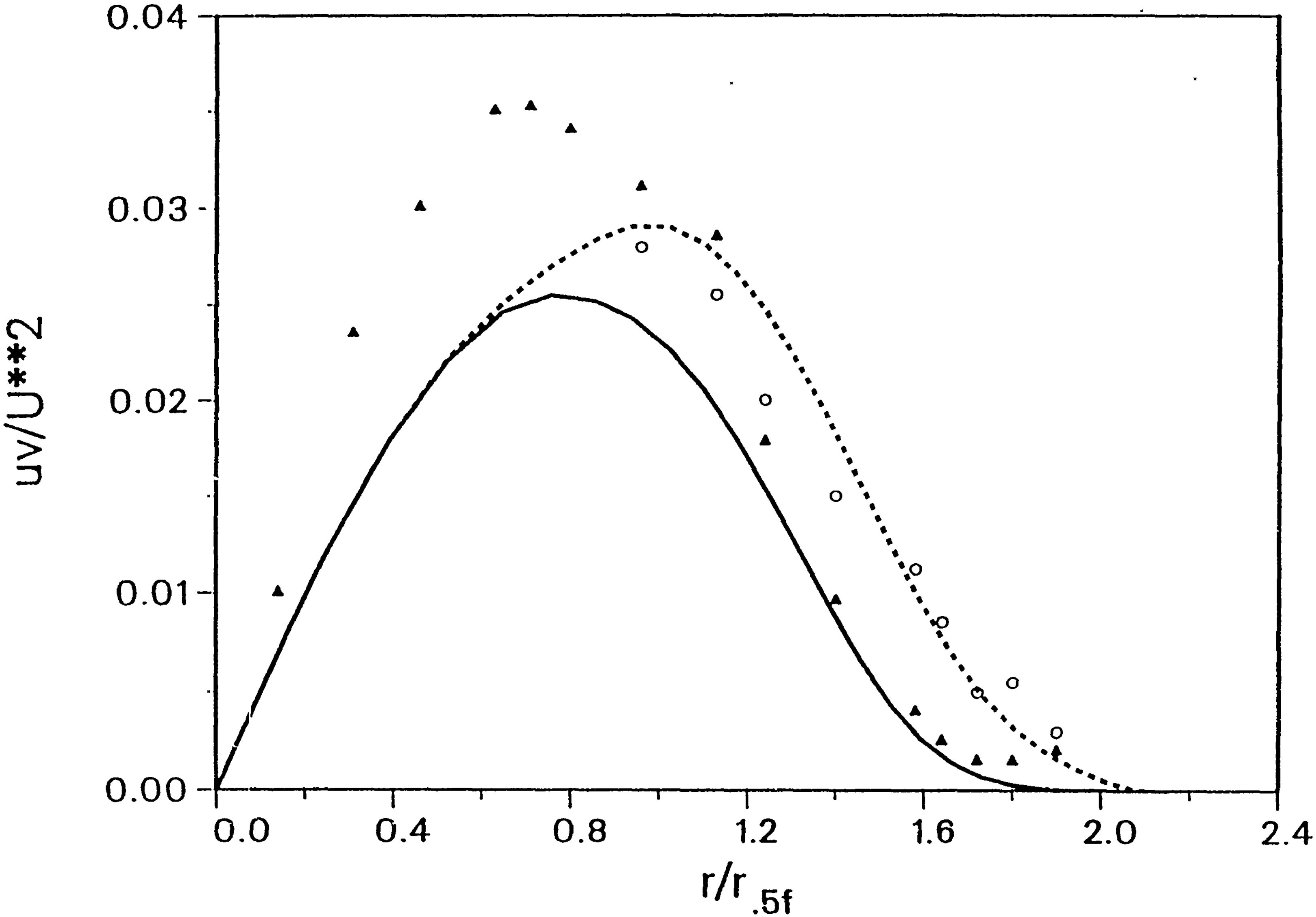


Fig. 4 Radial profiles of the covariance, conditional (--------) and unconditional (- - - -).

Dr. J.-Y. Chen of Sandia National Laboratories has made some preliminary calculations of a jet using this new source model with a conditional second order closure model developed previously [31]. For these calculations $A_t = 0.37$, $C_d = 0.25$ and l_γ is defined by

$$l_\gamma = \int_0^\infty \gamma\,(1-\gamma)\;dr,$$

where r is the radius. Some results from these calculations are shown in Figures 3 and 4.

Figure 3 shows radial profiles (normalized by the half radius) of conditional and unconditional mean axial velocity normalized by the center line value and the γ profile. The points shown are experimental data from Antonia, et al. [32]. Covariance model predictions are compared with data [32] in Figure 4. While refinement of the model is needed and better agreement for the covariance is desired, these results are encouraging.

To end this section it is noted that fractal modeling ideas have been taken up by others [33, 34].

Conditional Velocity Measurements

In premixed flames the flamelet is a thin sheet separating cold reactants from hot products. Since the kinematic viscosity is much larger in products than in reactants one expects the turbulence to behave differently in the two regions. Furthermore changes in turbulence occur across the flamelet; there is flow acceleration normal to the flamelet, thermal expansion across the flamelet reduces turbulence levels, while turbulence may be generated in the flamelet. Models have been proposed which to various degrees account for these different processes (e.g., [35]). Also there have been reports in the literature of conditional velocity statistics [36, 37].

We have develop a method for making very sophisticated conditional velocity measurements which has provided unique information on the velocity fields in V-flames and new insight into the coupling between the velocity field and flamelets [38, 39]. The key to our method is the simultaneous measurement of velocity and of the spatial position of the flamelet. A schematic of the experimental apparatus for these measurements is shown in Figure 5.

Velocity is measured by a standard two-color, two-component laser doppler velocimeter (LDV). The laser is a medium power argon ion laser. One of the beams used to measure the lateral velocity is frequency shifted by a Bragg cell to remove directional ambiguity. A beam expander is used to provide a tight focus in the LDV measurement volume and to improve the flatness of the interference fringes in the measurement volume. Scattered light from the LDV seed particles is collected at approximately 45 degrees from the axis of the laser beam, and the effective spatial resolution of the measurements is approximately 0.5 mm. As described below the seed particles are a combination of silicon oil mist and Zr_2O_3. Care is taken in adding the seed to the flow and with the optical alignment such that very good signal-to-noise ratios are achieved. Two counter processors are used to determine the doppler frequency, and the data are transferred to a laboratory

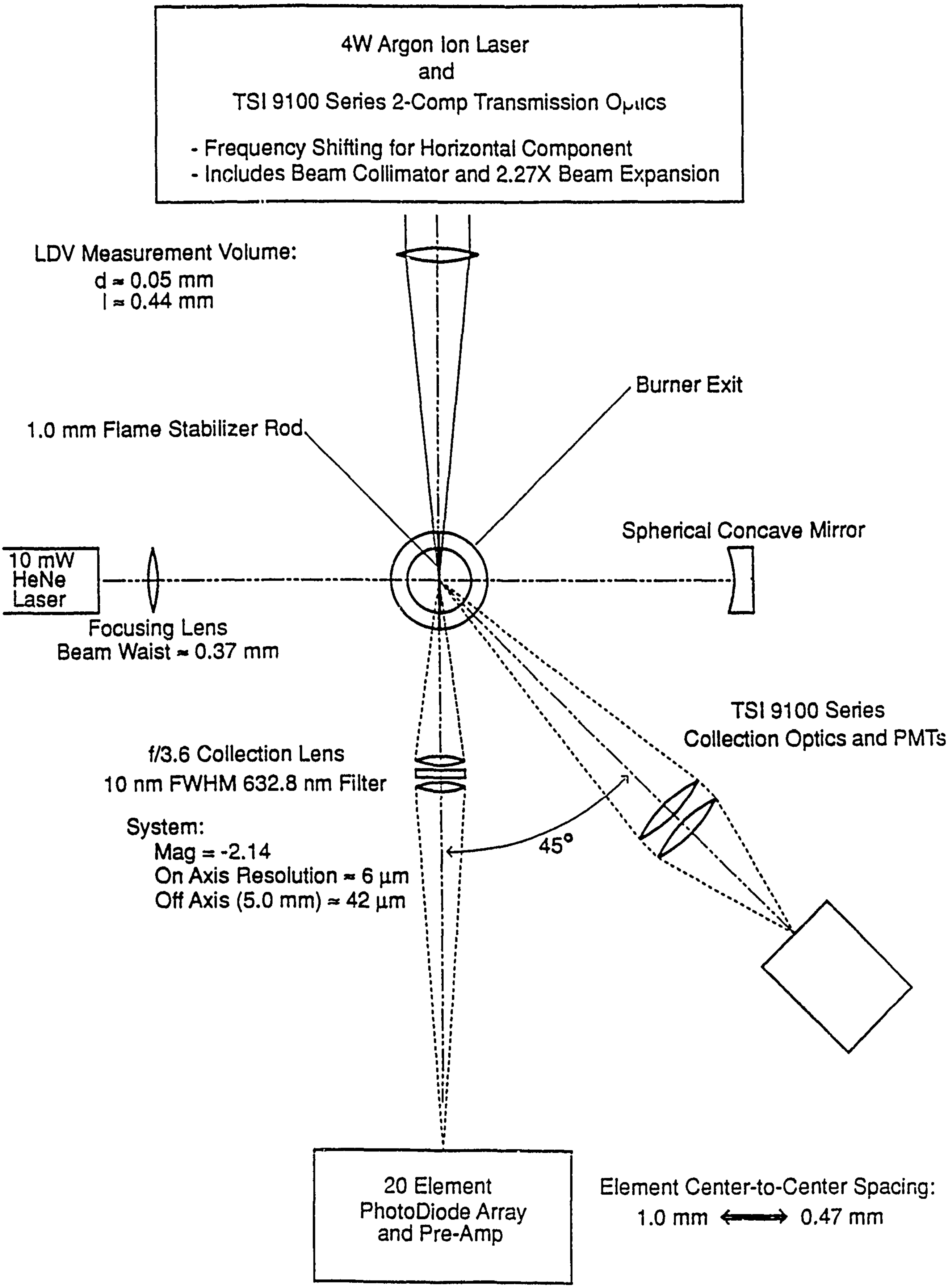


Fig. 5 Schematic of the apparatus for "fully" conditional velocity measurements.

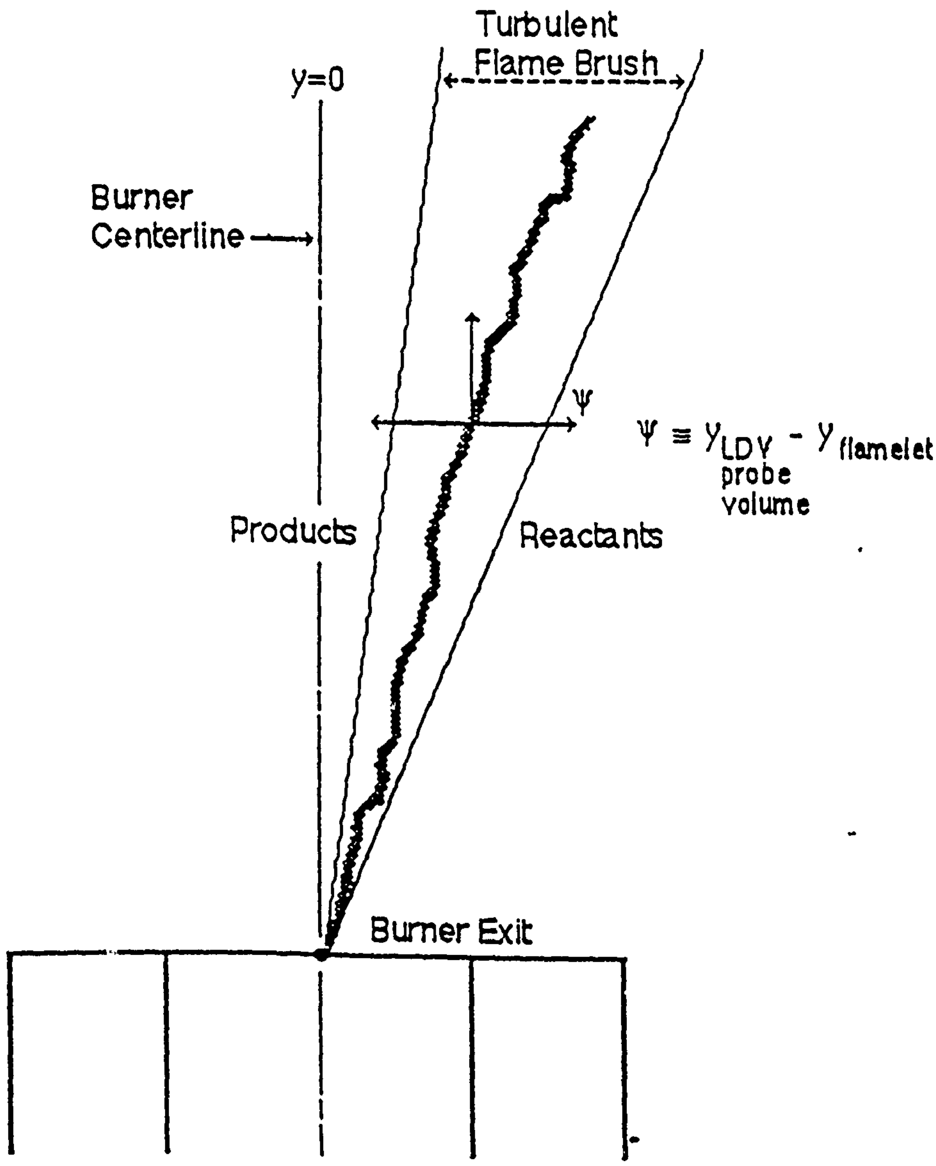


Fig. 6 Schematic of the V-flame burner showing the ψ coordinate system.

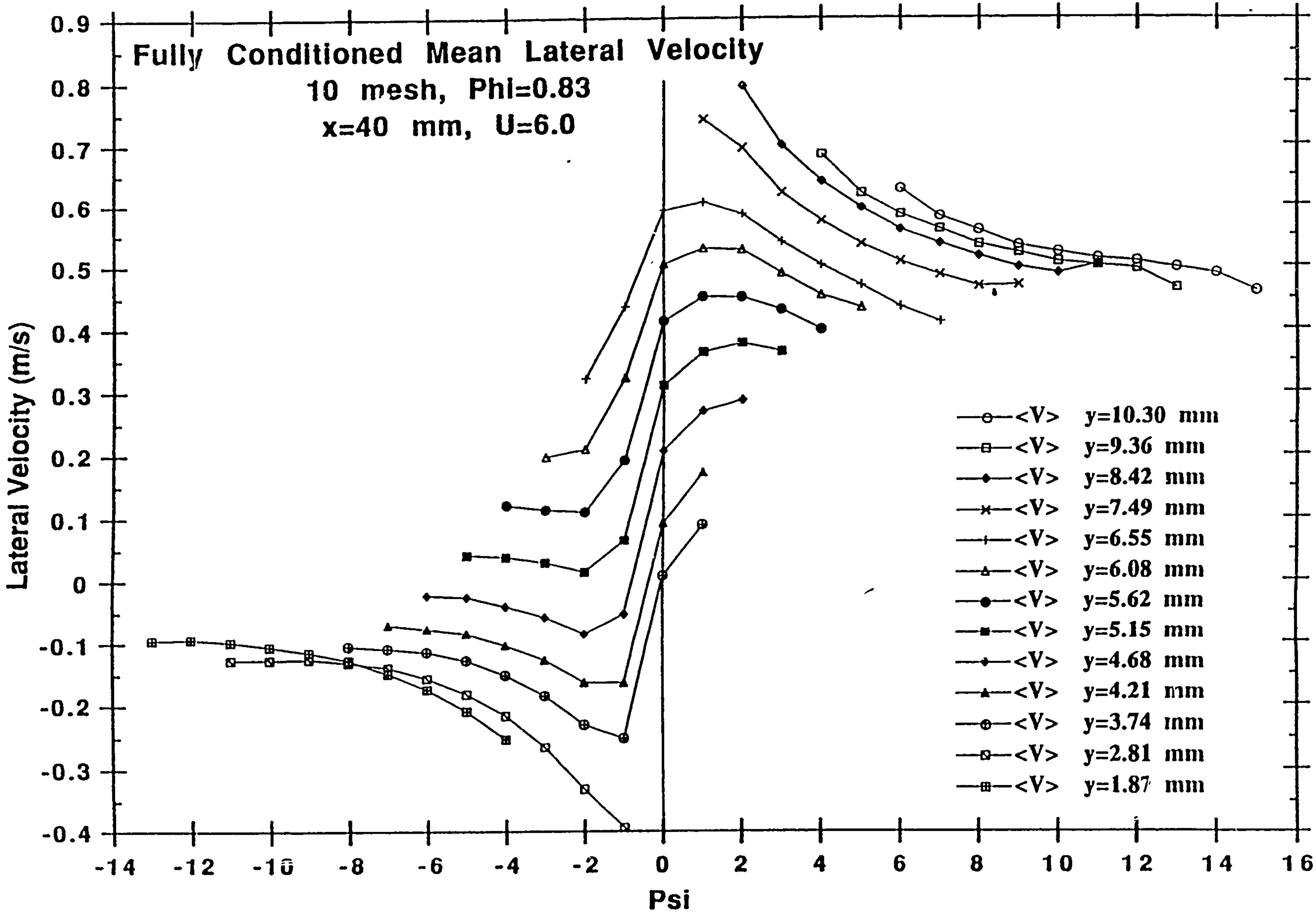


Fig. 7 "Fully"- conditional mean lateral velocity in $\phi = 0.83$, CH_4 - air, V-flame. Measurements made 40 mm downstream of the turbulence generating grid. y denotes the lateral position of the LDV measurement volume measured from a vertical plane containing the stabilizer rod. Positive velocities are directed away from the plane containing the rod stabilizer.

computer as digital words through an interface which also transfers the flamelet position signal.

The flamelet position along a line defined by a he-ne laser beam is measured by a 20-elemen*, linear-array, diode detector imaged at right angles onto the laser beam. The reactants are seeded with a fine oil mist which evaporates at approximately (within a narrow range) 650 K thereby marking reactants with seed but not marking products. The detector elements see either high signals from scattering in reactants or low signals from scattering in products, and thus the transition from high to low marks the location of the flamelet along the laser beam. For conditional velocity measurements the flamelet position signal (from the diode array) is recorded along with each validated velocity measurement.

Since the oil seed evaporates in the flamelet it can only be used to measure velocities in the reactants. A refractory seed, Zr_2O_3, is added to the flow for velocity measurements in product gases. Refractory seed concentrations are low compared to the oil mist and the scattering due to refractory seed does not influence the flamelet position measurement described above. Experience has shown that large oil mist and refractory particles (greater than a few microns) suffer from inertia and add noise to the scattering signals, both flamelet position and LDV. To avoid the resulting problems it is found to be necessary to remove the larger particles and droplets by use of cyclone classifiers on both seed flows. This step is important to obtaining good results.

Acquisition of simultaneous flamelet position and gas velocity data allow for the calculation of "fully"-conditional velocity statistics; that is one can obtain velocity statistics conditional on the position of the flamelet alone the line defined by the laser beam. From "fully"-conditional statistics one can obtain measures of the mean velocity jump across the flamelet and of changes in turbulence intensity and Reynolds stresses. One is also able to obtain normal or "simply" conditional statistics as well. Conditional statistics for premixed flames have been reported previously [36, 37]. However the present method has certain advantages over previously employed methods. Cheng and Cheng and Shepherd [36] infer conditional statistics by measured velocity pdf's. Cheng makes used of the bimodality of pdf's obtained with refractory seed to separate the pdf into two mono-modal pdf's, a method which is limited to conditions where the observed pdf's are markedly bimodal. Cheng and Shepherd obtain pdf's with oil mist seeding, which should correspond to reactant flow velocities only, and with refractory seed. To obtain a product only pdf the two measured pdf's are subtracted, one from the other. Before subtraction the two pdf's must be scaled appropriately, and this is done with an independently measured mean progress variable. Relative to the present method both of these methods are indirect. Gulati and Driscoll [37] used a combination of molecular Rayleigh scattering and LDV in their measurements. To avoid complications from particles scattering there is a lag of 250 μsec between the LDV measurement and the Rayleigh measurement of gas density. In certain flames this delay is insignificant, but in others, such as our V-flames, such a long delay is significant. We believe that the method described here for conditional measurements avoids both of these limitations and therefore is of more general applicability for conditional measurements as well has having the unique capability of making "fully"-conditional measurements for conditions under which flamelets exist.

Figure 5 is a schematic of the apparatus being used to make measurements in V-flames, while Figure 6 is a schematic of the V-flame which shows the coordinates used to define the "fully"-conditional statistics. ψ defines the instantaneous lateral position of the flamelet relative to the LDV measurement volume; ψ positive denotes the LDV measurement volume in reactants and negative denotes measurement in products. The spatial resolution of the flamelet position measurement is approximately 0.5 mm as is that of the velocity measurement. The "fully"- conditional statistics may be viewed as being obtained in the following way. Let $P(u,v,\psi)$ be the joint probability density function of the axial and lateral velocities and flamelet position, ψ. The velocity statistics are appropriate moments of this pdf with ψ integrated over a "bin" of width $\Delta\psi = 0.5$mm. For example the conditional mean lateral velocity at Ψ, $\langle v \rangle^{(\Psi)}$ is defined by

$$\langle v \rangle^{(\Psi)} = \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} \int_{\Psi - \Delta\psi}^{\Psi} v \, P(v, u, \psi) \, d\psi \, du \, dv.$$

As an example of what can be done, $\langle v \rangle^{(\Psi)}$ for a CH_4 - air flame at different lateral LDV measurement locations and a fixed axial location are presented in Figure 7. In this figure one notes that 1) the "fully"-conditional velocity profiles are similar at the different lateral locations, 2) there is a distinct drop in mean velocity across the flamelet and 3) that there is acceleration away from the flamelet. Among other things these observations imply that there is a significant instantaneous pressure gradient across the flamelet and that in the mean the acceleration associated with this pressure gradient is independent of lateral position in the turbulent flame brush. Some flow acceleration is to be expected if the flamelet model is valid. Data of the type shown here will help us learn about this acceleration and help incorporate its effects into turbulent combustion models.

C. **PUBLICATIONS AND REPORTS** (funded solely or in part by ARO)

Theses and Student Reports:

"Measurements to Determine the Fractal Character of Premixed V-flames", S. M. Hilton, Master of Engineering Report, May 1987.

"Point in Time Measurements of the Fractal Dimension of Premixed Turbulent Flames", T. Lamb, Master of Engineering Report, May 1987.

"A Determination of the Fractal Behavior of Constant Property Surfaces in Turbulent Reacting Flows Using a Laser Tomographic Analysis", G. F. Halow, Master of Engineering Report, July 1987.

"Fractal Analysis of Time-Series Measurements of Premixed Turbulent V-Flames", D. Goldfarb, Master of Engineering Report, August 1988.

"Time-Series Measurements in Premixed, Turbulent, V-Shaped Flames", H. L. M. Ozem, M. S. Thesis, January 1990.

"Time-Series Measurements of the Fractal Dimension of Surfaces in a Turbulent Jet Flow", J. Riley, M. S. Thesis, January 1991 (tentative).

"Fully-Conditional Velocity Measurements in Premixed Turbulent Flames", P. Miles, Ph.D. Thesis, June 1991 (tentative).

Reports and Extended Abstracts:

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